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Energy security and improvements in the function of diversity indices—Taiwan energy supply structure case study

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A B S T R A C T

Facing the risk and uncertainty inherent in social and economic development, many countries have adopted an energy supply diversification strategy in their energy security policy to control the energy import risk and cost to ensure that sufficient energy can be obtained at an affordable price level. Diversification helps the energy system respond to external changes and shocks. Diversification can also lessen the vulnerability of a single energy source to supply shocks and the market power of various energy supply sources. This study develops the "diversity reliability index" and "co-vary diversity reliability index" based on the Hirschman–Herfindahl and Shannon–Wiener indices, investigates the contribution of different energy sources to the energy system, and analyzes the covariance between various energies and their impacts on energy security to determine the impact of energy diversity in reducing the risk of energy supply shortages and cost fluctuations.

Contents

1. Introduction

In light of geographical inequalities and the scarcity of conventional fossil energy resources, as well as international energy price

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fluctuations, many countries have become involved in the global energy competition and regional energy strategic management to ensure energy supply security [1–4]. Among these nations, Asian countries, the energy demands of which continue to grow, while their energy supplies remain dependent on outside sources, have placed greater emphasis on energy security issues in their decision-making processes [5,6]. To date, many developed and developing countries, as well as international organizations, such as the EU, WEF, OECD, NATO, APEC and the G8, have incorporated energy security policies into their development policies [7].

Diversifying the long-term energy supply mix is an effective strategy for securing future energy supplies [8]. Additionally, imported energy supply security is often affected by factors beyond the control of importing nations, such as economic and trade difficulties, international politics, local environmental regulations and geographical location [9–12]. Many countries have adopted an energy supply diversification strategy in their energy security policies to reduce the risks associated with imported energy supplies and import cost fluctuations to ensure that sufficient energy can be obtained at affordable price levels.

Various indices have been developed to measure energy security at the national, regional and global levels, as well as for related issues, such as the independence and dependency of the energy system and the diversity of the energy mix and sources [6]. However, only a handful of studies have focused on the quantitative analysis of energy security to fulfill their energy policy analysis needs [13–15], and most diversity indices did not properly reflect the properties of various energy sources and their connections to the energy system, rendering these indices' estimations somewhat detached from the real-world state of energy security. This study investigates the inadequacy of the Herfindahl–Hirschman index (*HHI*) and Shannon–Wiener index (*SWI*) in interpreting energy diversity, proposes modifications of these indices and applies the modified indices to Taiwan's energy supply structure. Section 2 of this paper studies the correlation between energy security and energy diversity and analyzes the problems of present indices in assessing energy diversity. Section 3 explains Taiwan's energy supply situation, energy security policy and challenges. Section 4 proposes the modification of the *HHI* and *SWI* indices. The effectiveness of the revised indices is evaluated in Section 5 using Taiwan as a case study.

2. Energy security and diversity indices

2.1. Energy security and diversity

Defining energy security is not an easy task, for its definition varies with the time, place and purpose for which it is defined [5,11,16]. The basic dimensions of energy security include the following: risk management to reduce energy supply shortages, the reduction of imported energy vulnerabilities, the effectiveness of energy policy implementation, the integration of energy development goals in different terms and control over different markets [7].

Due to different endowments in natural resources, different countries may have different foci in their energy security policies; regardless, the basic concept of energy security is to provide affordable, accessible, efficient, environmentally friendly and acceptable energy service to consumers and to ensure the continuous supply of energy commodities and services such that social stability, economic growth and sustainable development can be maintained [17,18].

Unfortunately, the conventional concept of energy security is not sufficient to keep pace with the emergency of the diversified global energy market, cross-border energy transmission and consumption conflicts and the increasing importance of climate change and global environmental issues [12]. Moreover, in light of the close relationship between energy and the environment, international environmental conventions and domestic environmental regulations both have direct impacts on energy use [19,20].

Climate change has a significant impact on global energy resources, energy supply and energy consumption, especially on renewable energies, such as conventional hydrodynamic, wind and solar power [21,22], and also influences policy planning directions. However, if the GHG emission reduction issue incorporates energy policy strategy and security concerns under the premise that energy security equals national security, the GHG emission reduction strategy would need to be adjusted [21,23–25]. This requirement shows the close relationship between energy security and economic development, technological innovation, society, culture, environmental protection and international politics [26].

The basic concept of diversity is to avoid "putting all the eggs in one basket" [27]. In the fields of biology and ecology, diversity has been thoroughly discussed. From the evolutionary viewpoint, diversity provides more options for the evolutionary process to cope with environmental change [28]. Diversity can improve system stability. Therefore, the "diversity–stability hypothesis" emphasizes that a diversified system can return to the steady state faster after disturbances because there are multiple species to substitute one other [29–31]. The diversity of interacting components is helpful in establishing feedback loops for the ecosystem's resource management mechanism [32,33]. The diversity of the feedback loops and the speed of energy and resource flows can both improve the resilience of the eco-system [34], and this resilience in reorganization and adaptation can maintain system stability [35,36].

In recent years, studies investigating diversity have expanded into the fields of politics, management, public policy and science [37]. Since the 1950s, economists have paid attention to the correlation between economic systems' diversity and stability and their development policies and have developed many theories. The function of diversity in the socio-economic system exhibits many similarities with its role in both the ecological and social fields.

The diversity of the socio-economic system includes the combination of different meanings of efficiency, the improvement of adaptive flexibility and evolutionary potential. These factors provide the socio-economic system with the ability to generate new targets and properties in response to changing trends and are important strategies to reduce risk [28,38].

Matutinović [39] analyzed the function and structure of the ecosystem and proposed the socio-economic system diversity hypothesis, which states that to maintain the coherence and integrity of the socio-economic system, the system should maintain diversity. If diversity drops below a certain threshold, it may cause instability and crash the global economic system.

Social economists also believe that the socio-economic system would be more resilient if its participants were diversified in philosophy, resources, perspectives, methods and reactions. Templet [40,41] defined the diversity of the economic system as "the number and equitability of energy flow paths within an economic system" from the ecological economics point of view.

In the viewpoint of industrial ecology, a diversified and interdependent industrial system has better recycling functions for waste, byproducts and energy [42–45]. In recent years, studies on complex adaptive systems (CAS) have extended to the ecosystem, biospheres, economic systems and organizations and have emphasized how systems respond to external changes through their complex structures and interactions. Among them, Levin [46] notes that diversity is an important element in a complex system.

Diversity is important to energy security. Energy security can be affected by various technical, human and natural risks, of which human and natural risks are related to the availability and accessibility of energy [18].

Stirling [47] points out that diversity has four major advantages: (1) diversity is the key to promoting growth and innovation; (2) diversity is the hedging instrument for the blind spots of decision-making; (3) diversity can reduce the negative impact of supply shocks and embargos; and (4) diversity is a method for harmonizing social differences. Diversity can also help energy systems effectively respond to the changes and shocks of the external environment, such as fluctuations in the global market, changes in environmental regulations, price changes for a specific energy and supply shortages [48]. Diversity of energy supply sources can reduce vulnerability to the disruption of a single supply source and also reduce the market power of each supply source; thus, the risk of rising energy prices in production and services can be reduced [49].

The benefits of diversity are especially significant when uncertainty surrounds shortages of resources or goods. Generally speaking, the greater the dependence on imported energy or a single energy source, the greater the risk to energy security. The risk of energy supply interruptions come from the concentration of energy supply sources and the possibility of supply interruptions to each energy source. Therefore, a system that is highly import-dependent may not be in a high-risk state, if its energy supply sources and types are diversified [50]. Diversification and localization of energy systems is the best approach to simultaneously improve energy security and balance energy needs, environmental needs and sustainable development [51]. However, the concept of diversity varies in both definition and purpose, and a lack of consensus remains surrounding the definition of diversity in the field of energy policy decision-making [52].

Many countries have regarded energy diversity as a major energy security policy measure [53]. Confined to the geographical inequality of conventional fossil energy reserves, changes in the political and economic situations of energy exporting countries often arouse the attention of countries with scarce energy resources. Finding ways to reduce the concentration of imported sources of fossil energy has become an important policy direction for reducing the risk of energy security in energy-importing countries [25]. Especially in the power generation sector, promoting fuel diversity through a combination of different power generation technologies is helpful for achieving a balance between reducing cost and risk and has gradually gained the attention of decision-makers [54]. Energy diversity has the advantages of reducing long-term average costs, reducing risk and dependence on a specific import source and being environmentally friendly [55]. Policymakers, however, often regard energy security as equivalent to energy independence, and many policies focus on the promotion of indigenous energy supplies while ignoring the importance of risk management through increasing the diversity of imported energy supply sources and improving inter-substitution among different types of energies [56]. Additionally, energy market regulators and/or policymakers often ignore the importance of diversity in the energy market and do not design appropriate market mechanisms to guide investors toward the diversification of the energy mix, preventing the development of overall energy security through the energy market [20,47,57–60].

Quantitative assessments of energy security have begun to appear in recent decades [61–64]. Recently, increasing numbers of studies have investigated the assessment of energy security and applied various methods to estimate the security of energy import sources [56,65,66]. Multiple indices have been developed to measure the diversity of energy supply sources, dependence on imported energy, political stability [8,67] and oil market fragility [66]. There are two types of indices used to assess energy security. One type is used to measure the degree of independence of the system, while the second is used to measure the system's vulnerability. However, there is still no standard method for measuring the security of the energy mix using energy security indices [11,25,68]. Sovacool and Mukherjee [69] measured the energy security performance of 18 countries, including the United States, Japan, the European Union, Australia, China and India, from 1990 through 2010 with 320 simple indices and 52 integrated indices falling in the dimensions of availability, affordability, technology development and efficiency, environmental and social sustainability and regulations. Xia et al. [70] used energy diversity indices and oil-independence rates to analyze the energy security, efficiency and carbon emissions of the Chinese industrial sector. Kruyt et al. [11] summarized energy security indices developed in various recent studies, classified them as simple or integrated indices, grouped them into four dimensions, namely, availability, accessibility, affordability, and acceptability, and assessed the effectiveness of different energy policies based on their improvement of energy security in geopolitical, economic and environmental aspects of regional and global energy. Roques [20] applied the Mean–Variance Portfolio optimization theory and Monte Carlo method to conduct a two-stage simulation on the return on investment of gas-fired, coal-fired and nuclear power generation units. The simulation result is used as the input parameter for the study of the optimal base load combination of power generation units in the liberalized electricity market, as well as the impacts of fuel prices, electricity prices and carbon prices and their correlation with the abovementioned optimal base load combination. Augutis et al. [71] constructed a quantitative energy security indicator system encompassing technical, economic and socio-political dimensions to assess the degree of energy security in different scenarios. Vivoda [72] constructed energy security assessment tools in eleven dimensions, including energy supply, demand management, efficiency, economy, environment, human security, military security, domestic, social and human politics, international politics and science and technology. Skea [73] applied the modified Simpson/*HHI* coefficient and Stirling indices to explore the issue of disparity and discussed options for policy tools promoting energy diversity.

2.2. Diversity index analysis

The energy and ecological diversity indices are similar in their calculation methods. This study summarizes all types of diversity indices and their application areas in Table 1; the development of diversity indices is described in Margurran [74] and Rosenzweig [75]. Diversity indices have been applied widely in various fields. Among these indices, the Hirschman–Herfindahl index, Shannon–Wiener index and integrated multi-criteria diversity index are the most commonly used and discussed in energy fields. Therefore, the discussion below will focus on these three indices.

2.2.1. Hirschman–Herfindahl index

The Hirschman–Herfindahl Index (*HHI*) was developed by Hirschman [76] and Herfindahl [77] to calculate degrees of concentration (see Hirschman [78]). The *HHI* is commonly used to analyze the dispersion of market power in a single market, such as the electricity market [79,80]. The *HHI* has proven to be a relatively reliable index and can satisfy all the requirements for measuring concentration proposed by Hall and Tideman [81], Hannah and Kay [82], and Encaoua and Jacquemin [83]. *HHI* has also been incorporated into the U.S. horizontal merger guidelines. According to Section 7 of the of U.S. Clayton Act, large enterprises should submit an application to the U.S. Department of Justice (DOJ) and Fair Trade Commission (FTC) before they merge. After assessing the impact of merger behavior on competition, the FTC will decide whether the application is allowed or rejected, and the *HHI* is one index used to measure the degree of market concentration in this process. The *HHI* is the square summation of the

Table 1
Diversity indices and application fields.

Index	Formula	Application fields
Gini	$\frac{\sum_{ij=1}^{N} \lvert p_i - p_j \rvert}{2N} / 1 - \sum_{i=1}^{N} p_i^2$	Economic statistics, wealth and income distribution
Herfindhal–Hirschman, see Hirschman [76]	$\sum_{i=1}^{N} p_i^2$	Economics, market power assessment, energy diversity
Simpson [96]	$\sum_{i=1}^{N} p_i^2$	Ecology, biodiversity
Shannon–Wiener, see Shannon and Weaver	$-\sum_{i=1}^{N} p_i \ln(p_i)$	Ecology, biodiversity, energy diversity
Rao [91]	$\sum_{ij=1, i \neq j}^{N} d_{ij} p_i p_j$, d_{ij}: difference between option i and option j	Population biology
Stirling [47]	$\sum_{ij=1, i<j}^{N} d_{ij} p_i p_j$, d_{ij}: difference between option i and option j	Energy system, technology assessment
Shannon Weiner–Neumann, see von Hirschhausen and Neumann [97]	$-\sum_{i=1}^{N} b_i p_i \ln(p_i)$,$b_i$: political stability index ofenergy exporting country $-\sum_{i=1}^{N} b_i (1+g_i) p_i \ln(p_i)$,$g_i$: share in indigenous energy supply	Energy system
Ricotta and Avena	$-\sum_{i=1}^{N} p_i \ln(k_i)$,$k_i$: standardized weight of option differences, $\sum k_i = 1$	Ecology, biodiversity
Shannon, see Jansen et al. [8], Jansen and Seebregts [98]	$-\sum_{i=1}^{N} c_i p_i \ln(p_i)$ $c_i = 1 - m_i(1 - S_i^m / S_i^{m,\max})$ $S_i^m = -m \sum_j h_j m_{ij} \ln m_{ij}$ $-\sum_{i=1}^{N} c_i^4 p_i \ln(p_i)$ $c_i^4 = 1 - (1 - r_{jk})(1 - m_i)^* 1 - m_i(1 - S_i^{m**} / S_i^{m**,\max})$	Energy system
Ricotta and Szeidl	$-\sum_{i=1}^{N} p_i \ln\left(1 - \sum_{i \neq j}^{N} d_{ij} p_j\right)$	Ecology, biodiversity
Stirling [90]	$\sum_{ij=1, i<j}^{N} (d_{ij})^{\alpha} (p_i p_j)^{\beta}$	Energy system, technology assessment

market share of each company in the industry. If $HHI < 1000$, the market is complete and sound and market power is dispersed. If $1000 < HHI < 1800$, market power is moderately concentrated. If $HHI > 1800$, the market power is excessively concentrated. According to FTC guidelines, the *HHI* should not exceed 1800 after the merger, and the difference in the *HHI* before and after the merger should not exceed 100; the difference for the merger of banks should not exceed 200.

In addition to assessing market concentration, the *HHI* can also be used for diversity analysis. The equation of the *HHI* is the similar to that of the Simpson index, and both indices belong to the Hill index family [84]. From the relative abundance viewpoint, the *HHI* emphasizes abundant species [85]; that is to say, the *HHI* emphasizes options that occupy a larger share of the structure. In energy systems, the energy or energy supplier which is greater in amount or occupies a greater market share usually has a greater impact on energy security. Therefore, the *HHI* is suitable for the risk analysis of energy systems or markets [65]. Blyth and Lefěvre [49] combined the *HHI* and the political risk ranking index of energy exporting countries to analyze the impact of various energy suppliers on market stability. Gupta [66] used the *HHI* to analyze the risk of oil supplies. Frondel et al. [86] combined the *HHI* and the political stability index to study domestic energy supply security. Le Coq and Paltseva [65] combined the *HHI* and the analysis of political risk for energy importing countries, the risk of imported energy transmission and the economic impact of energy supply shortages to analyze the short-term imported energy supply risk of the EU.

2.2.2. Shannon–Wiener index

The Shannon–Wiener index (*SWI*) is derived from the concept of entropy in the Second Law of Thermodynamics. Entropy, a physics concept, is used to describe the degree of chaos in a system; specifically, the more chaotic the system, the greater the degree of entropy. Shannon [87] used entropy to describe informational uncertainty and thereby defined the *SWI*. The *SWI* also belongs to the Hill index family [84]. From a relative abundance viewpoint, the *SWI* places greater emphasis on rare species [85]. The *SWI* is applied in the fields of biology, ecology and economics to calculate diversity [88]. The formula for the *SWI* is

$$SWI = -\sum_i p_i \ln p_i,$$

where p_i stands for the share of option i. Higher *SWI* values are associated with greater diversity in the system. When all options occupy an equal share, the *SWI* will be at the maximum.

Many studies have applied the *SWI* in the field of energy diversity and energy security. Jasen et al. [8] modified the Shannon–Wiener index and developed various diversity indices to consider the independence of imported energy sources, the political and economic situations of import sources and the risk of resource depletion. Costantini et al. [89] used the Shannon–Wiener index to analyze energy dependence and vulnerability in various scenarios. Bhattacharyya [50] used the *SWI* and *HHI* to calculate power generation structure changes from 1995 to 2006 in Europe. Hickey et al. [88] chose the Shannon–Wiener index to measure the diversity of power supply combinations in the American state of Illinois after reviewing portfolio theory, real options theory and other diversity assessment methods. Van Vliet et al. [6] compared the Western European countries to major Asian countries using the Shannon–Wiener diversity index and the import independence index, which was developed by Jansen et al. [8] based on the Shannon–Wiener diversity index.

Stirling [47] noted that the Shannon–Wiener Index is the best simple diversity index. This index can reflect both the variety and the balance of the system but is less ideal in the assessment of disparity. Differences in the value of Shannon–Wiener index could not properly reveal real impacts on diversity [27]. Because of the method's shortcomings in assessing disparity, the adequacy of energy classification will affect the results of the Shannon–Wiener Index. Different energy mixes means different risks of energy shortages, but Shannon–Wiener diversity index does not take this difference into consideration [11].

2.2.3. An integrated multi-criteria diversity index

Stirling [47] defined diversity using three dimensions, namely, variety, balance and disparity. However, the *HHI* and *SWI* diversity indices cannot effectively reflect disparities, i.e., the degree of difference between two options. Therefore, Stirling [47,90] referred to the quadratic diversity index proposed by Rao [91] and developed the integrated multi-criteria diversity index using the

summation of the product of the difference between two options multiplied by the share of each option:

$$\sum_{ij=1,i<j}^{N} (d_{ij})^{\alpha}(p_i p_j)^{\beta},$$

where p_i is the share of option *I*, and d_{ij} is the Euclidean geometric difference between option *i* and option *j*. Yoshizawa et al. [92] perform a complete analysis of the calculation of the difference. α and β are the combination of 0 or 1, which reveals that the index focuses on variety, balance or disparity.

The integrated index is complete, parsimonious, transparent and robust and meets all consistency requirements. However, the quantification of the difference of the two options can be subjective, possibly complicating efforts to calculate this index [88]. Furthermore, this index ignores the substitutive and complementary relationship between energy and technology options in real energy markets, and the improvement of diversity may also increase the risk and cost of energy acquisition and consumption.

The application of diversity indices still faces questions and challenges. Odum [93] noted that the diversity index may cause confusion on three identical ecological concepts of diversity, variety and evenness. Roy et al. [94] believed that a single value diversity index could not express the structural information of an ecosystem. This researcher argued that such indices as the *SWI* and the Simpson diversity index mainly reflect the proportion of species and cannot provide information on species changes or the degree of change. Yue et al. [95] also asserted that the diversity index's assumption that each species in the community is of equal value is erroneous because the keystone species should be of greater importance than other species in the community.

Regardless of the inadequacies of the *HHI* and *SWI* in the interpretation of diversity, they are more transparent and objective in data acquisition and calculation compared to the integrated multi-criteria diversity index, and these indices have greater room for further modification. Therefore, this study explores the meaning of diversity and energy security based on the *HHI* and *SWI* and modifies both indices to improve their ability to interpret disparities in energy security.

2.2.4. Improvement of diversity index

The above energy diversity indices regard each type of energy as independent and do not consider the complementary and substitutive relationships between energies or their correlations in the energy market. As shown by historical price data on conventional fossil fuels, the price changes of crude oil, natural gas and oil are highly correlated. If these energies are to be used as alternatives for one another in energy security policy, the energy cost and requisition risks will not be effectively reduced; in other words, if the selected energies are positively correlated in price or demand, energy security risks cannot be reduced effectively, even though the energy supply structure appears to be diversified under the auspices of the energy policy. During energy security strategy planning procedures, the risks of various energy sources and technologies can be categorized, but not all risks can be reasonably quantified. Therefore, the design of energy diversity indices can be further improved to control the various risk factors properly, as well as their correlations in energy supply planning and energy security decision-making processes, and ensure that the risk energy supply portfolio can be minimized and that policy measures can effectively improve energy security.

Furthermore, energy diversity indices assume that each energy source is identical, and consequently, they cannot properly reflect the characteristics of the various types of energies in the energy system. For instance, the stability of renewable energy prices makes renewable energy a hedging instrument in times of fuel price fluctuations [99]. Renewable energy is indigenous and clean, and its production costs are not closely correlated with global fossil energy market trends. Therefore, increasing the share of renewable energy in the energy mix is helpful in reducing the risks stemming from changes in the price of imported energy [100].

However, contemporary quantitative studies on energy security tend to overlook the contribution of renewable energy in enhancing energy supply, price security and energy system dispatching security. However, the supply of most renewable energies is capital-intensive and passive and discontinuous; in the case of wind and solar energy, for example, the supply relies heavily on the weather and natural conditions. These characteristics make renewable energy unsuitable as a major energy source under present technological and cost constraints, although renewable energy carries low or even nonexistent energy price risk.

3. Energy supply trends in Taiwan

3.1. Energy supply trend analysis

In 1996, Taiwan's total energy supply was 81,438 thousand kiloliters of oil equivalent (KLOE), made up of 54.8% petroleum, 25.9% coal, 13.4% nuclear power, 5.2% natural gas (including LNG) and 0.6% hydropower. In 2011, the total energy supply reached 138,237 thousand KLOE, with the share of petroleum, nuclear power and hydropower decreasing to 46.2%, 0.3% and 8.8%, respectively, while the share of coal and natural gas (including LNG) increased to 31.4% and 11.8%, respectively. Additionally, although solar power and the thermal supply increased 57 thousand KLOE from their 1996 levels, their share of total power was only 0.08% in 2011; similarly, the wind power supply increased 143 thousand KLOE from 1996 for a 0.1% share of the 2011 total (see Fig. 1 [101]).

Classified into indigenous and imported energy, indigenous energy sources increased from 1471 thousand KLOE in 1996 to 2861 thousand KLOE in 2011, while imported energy sources increased from 79,967 thousand KLOE to 135,376 thousand KLOE over the same period. The dependence on imported energy increased from 98.2% in 1996 to 99.3% in 2011, indicating that Taiwan is highly dependent on imported energy [101].

3.2. Review of energy supply

Due to its lack of indigenous energy, imported energy made 99.3% of the total energy consumed in Taiwan in 2011. Additionally, as an isolated island, Taiwan cannot create a support system through cooperation with bordering countries, with the result that its energy security system is rather fragile. Taiwan's major source of petroleum imports is the Middle East, and its degree of dependence on Middle Eastern crude oil imports has reached 79.7%; Taiwan's coal is primarily obtained from Australia and Indonesia (adding up to 82.8%); the Middle East and Southeast Asia are Taiwan's main sources of imported natural gas (76.3%). In recent years, the fluctuation of international energy prices has not only caused problems in acquiring energy but has also increased the cost of energy imports for Taiwan because it is an international energy price taker with little or no bargaining power. The long-term trend of rising energy prices has been a great burden to industry and households. The ratio of energy imports to GDP has increased from 2.9% in 1996 to 13.6% in 2011, and per capita energy imports increased to NTD 80,711 in 2011 from NTD 10,633 in 1996 [101].

Taiwan's energy and power supply structure both depend heavily on fossil fuels, such as petroleum, coal, and natural gas.

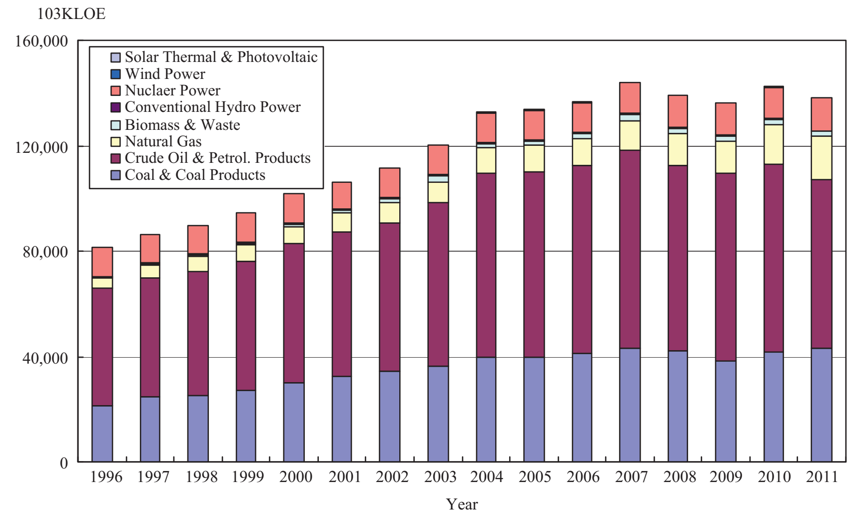

Fig. 1. Energy supply in Taiwan. Data *source*: MOEABOE [101].

Fossil energy accounted for 91.3% of Taiwan's total energy supply in 2011. Because conventional high-carbon energies are all imported from foreign countries, their supply is easily influenced by the fluctuation of international demand, production, price, and regional politics. High-carbon fossil energy is also a major source of greenhouse gas emissions, such as CO_2.

The production and consumption of fossil and nuclear energy will negatively impact the environment, human health, and quality of life, as well as ecological equilibrium and biodiversity. Thus, indigenous and decarbonized energy, such as renewable energy, should be the primary energy source in the future [102]. The higher the share of high-carbon fossil fuels in the energy mix, the greater the negative impacts on energy security and the environment; in other words, the share of high-carbon fossil fuels in an energy mix is inversely related to energy security [103]. Although coal is recognized as a high carbon energy source, in light of its advantages of low cost and abundant reserves, coal will retain a certain percentage of energy consumption through the improvement of power generation technologies using coal-fired and gas-fired units and carbon capture storage [104].

From the perspective of electricity generation structures, gas-fired units have the advantage of being clean and environmentally friendly, at least for now. However, the utilization of natural gas is also limited by its import source, LNG terminal capacity, loading capacity and inflexible contract terms; its generation cost is also significantly higher.

As for nuclear energy, although nuclear energy does not release carbon dioxide, the location of radioactive waste storage sites and overall nuclear safety are highly contentious issues with the public, especially in the wake of the Fukushima nuclear disaster, in response to which the Japanese government declared that it would “steadily reduce nuclear dependency and gradually move towards a nuclear-free homeland” in November 2011. Due to this decreasing reliance on nuclear energy, the proportion of nuclear energy used in the future will decrease, and existing nuclear power plants will be decommissioned.

Renewable energy is a renewable and indigenous energy source that is also more environmental friendly than conventional fossil energy. However, barring wind power, the development of most renewable energy sources is restricted by their relatively higher costs, which make them less competitive compared to traditional fossil energy. Additionally, under present technological constraints, renewable energy's discontinuous nature precludes it from being the predominant energy source.

With respect to coal, although it has the advantage of low cost and energy source dispersion, its pollutants, SO_x, NO_x and CO_2, are also relatively more harmful than those of other fossil energies. Therefore, the installation of coal-fired power generation facilities often faces protests from surrounding residents and environmental organizations and is frequently unable to be completed. This energy source needs a breakthrough in energy technology to overcome its present problems. Please refer to Table 2 for the energy characteristics and developmental disabilities of Taiwan.

3.3. Taiwan's energy diversity policy

Over 99% of Taiwan's energy is imported. Moreover, Taiwan's energy supply is heavily reliant on fossil fuel energy. Taiwan also faces the challenges of energy scarcity, fluctuating global energy prices, climate change, growing energy demand and public resistance to energy development projects and energy price adjustments. Taiwan's priority in energy development is to ensure energy security and satisfy its people's basic needs. To ensure a balanced and stable energy supply and demand in the short, medium and long terms, Taiwan issued the “Guideline on Energy Development” in 2012 to regulate energy policies, principles and strategies and to serve as the basis for general energy development planning.

Taiwan's energy security target is to establish a balanced energy supply and demand system that is affordable and low-risk; its policy principle is to stabilize the origin and channels of energy supplies, to ensure the balance of energy supply and demand and the stable operation of the system and to manage the system's risk. To fulfill these targets, Taiwan will pursue diversified and independent energy supply sources and a superior energy structure on the supply side. The following measures are proposed: (1) promoting international cooperation in energy development and technology; (2) encouraging energy industries to participate actively in the exploration, development, investment and procurement of energy resources domestically and abroad; and (3) diversifying the sources and methods of energy procurement to reduce energy supply risks. As for promoting the diversity of energy supplies, Taiwan aims to develop a clean, secure, independent, and sustainable low carbon energy system. Taiwant's strategies include [105]

(1) Gradually augmenting its renewable energy development targets on power generation and thermal utilization according

Table 2
Energy characteristics and development obstacles in Taiwan.
Source: 1.BP [106]. 2. OECD [107].

Type	Global reserve	R/P ratio	Energy characteristics and environmental impact				
			Application	Supply stability	Cost	Environmental impact & CO_2 emission	Development obstacles
Petroleum	1652.6 billion barrels	54.2	1.Industry and transport 2.Raw material	Medium; affected by regional politics	Medium	Medium	Limited reserve, increasing production cost, geopolitical conflict in oil producing countries, and growing price
Natural gas	208.4 trillion M^3	63.6	Power generation and industry	Medium; suffered tight LNG supply in Asian market, but benefited by rich shell gas supply potential	High	Low	Capacity of LNG terminal, capacity of loading
Coal	860.9 billion MT	112	Power generation	High; rich in reserves, and allocated in countries with stable political situations	Low	High; carbon emissions need to be solved by future CCS technology	High pollutant and carbon emissions, public resistance
Nuclear	5.5 million MT	100	Power generation	High; stable in supply source, and small in size, easy to transport and store	Low; if the cost of final treatment not included	No carbon emissions; nuclear safety is highly concerned; temporary and final disposal site need to be selected	Public concern of nuclear disaster, and the policy to steadily reduce dependence on nuclear energy
Renewable energy	-	-	1.Power generation 2.Alternative for petroleum	Low	High; averaged	No carbon emissions; environmental impact varies by case	Seasonal, weather, and geographical constraints; unable to be stable base load

to their potential and technological development and constructing the infrastructure for grid connection.

(2) Promoting the use of low carbon natural gas with consideration for its impacts on supply security and fuel cost.

(3) Flexibly adjusting coal consumption with regard to energy security and a stable power supply, and introducing clean coal and carbon reduction techniques for diminishing carbon emissions due to coal consumption according to the technology progress domestically and abroad.

(4) Reducing petroleum dependence on petroleum and promoting the development and application of alternative energy technique for petroleum.

(5) Ensuring nuclear safety and promoting a steady reduction in nuclear power dependence.

(6) Stabilizing the power supply, improving the power supply quality and encouraging the installation of dispersed power supply systems to balance regional supply and demand.

4. Methodology: Diversity indices

This study further modifies the *HHI* and *SWI* to solve their inadequacy in reflecting energy characteristics and correlation between various energies and total energy supply.

4.1. Energy supply diversity index (I_1)

This study is based on the *HHI* and *SWI* and uses the following formula:

$$HHI_1 = \sum_{i=1}^{I} p_i^2$$
$$SWI_1 = -\sum_{i=1}^{I} p_i \ln p_i,$$

p_i: the share of energy i in total energy supply.

4.2. Energy supply diversity and reliability index (I_2)

This index refers to the adjusted Shannon Wiener–Neumann index of Von Hirschhausen and Neumann [97], which can reflect the contributions of autonomous indigenous energy on energy security and adopt the supply capacity of various energies into its consideration of reliability. This design can further elaborate on the reliability advantages of conventional fossil fuels, due to their technological maturity, as well renewable energy's limited ability as a stable energy source. These properties can resolve the problem that present diversity indices often overlook: the disparities between various energies in their contribution to the security of the overall energy system. The formula is as follows:

$$HHI_2 = \sum_{i=1}^{I} (1-q_i)^*(1/f_i)^* p_i^2$$
$$SWI_2 = -\sum_{i=1}^{I} (1+q_i)^* f_i{}^* p_i \ln p_i,$$

p_i: the share of energy i in the total energy supply.
q_i: the share of energy i in the total indigenous energy supply.
f_i: the supply capacity of energy i.

4.3. Energy supply diversity and reliability variance index (I3)

This study applies the Mean–Variance Portfolio (MVP) theory of Markowitz [108], which is used to measure the impact of correlation between various energies on the energy security risk. By analyzing the Variance–Covariance Matrix, the theory derives the efficiency frontier by rate of return and standard deviation. This theory can maximize the rate of return under the circumstances of fixed risk levels or minimize the risk when the rate of

return is fixed. The risk in this theory refers to idiosyncratic or unsystematic risk. Bar-Lev and Karz [109] first applied MVP theory to the fuel procurement of the American electric utility industry [110]. This theory also applies to research in energy fields, such as energy structure, electric fuel mix and the optimization of renewable energy portfolios [20,53,57,111].

This study uses the correlation coefficient to compare the variance between each pair of imported energies and to manage the impact of the inter-correlation on the risk of the overall energy supply system [112,113]. The price variation is used to represent the characteristics of energy supply and demand and to explain the correlation between two different energies with the price correlation coefficient. If the prices of two different energies are positively correlated ($0\le\sigma_{ij}\le1$), the risk would be higher under an equal rate of return. Contrastingly, if energy prices are negatively correlated ($-1\le\sigma_{ij}\le0$), the risk would be lower.

The risk of an energy portfolio depends on the size and sign of the correlation coefficient. When the correlation coefficient σ_{ij} is positive, the risk increases, and as σ_{ij} approaches −1, the risk decreases. From the perspective of reducing energy portfolio risk, if the energy structure contains more substitutive or risk-free combinations within the system, the risk will be lower. Contrastingly, the complementary energy structure will be higher in risk. Due to the indigenous and clean characteristics of renewable energy, its cost will not co-vary with that of conventional fossil energy. For instance, wind power has no fuel costs; compared to conventional thermal power generation technology, the latter will be inevitably exposed to a higher risk of fuel cost fluctuations. As a result, during periods of drastic change in fuel prices, the stability of renewable energy can be used as a hedging instrument. This study considers renewable energies, such as wind power, solar power, waste disposal, biofuel and hydropower, to be risk-free options ($\sigma_{ij}=-1$); the reliability issue of renewable energy will be discussed by the reliability index (I_2).

In MVP theory, consider a portfolio composed of n assets with fixed returns to minimize the risk, which can be shown by non-linear programming:

$$Min\sum_i p_i^2\sigma_i^2+\sum_i\sum_j p_ip_j\sigma_{ij},$$

where p_i is the share of asset i, and σ_{ij} is the covariance of asset i and j.

$p_i^2\sigma_i^2$ indicates uncertainty risk caused by the variance of option i and can be considered to be a reliability indicator of HHI_2. $p_ip_j\sigma_{ij}$ is the risk caused by the covariance of various energies, and the formula is as follows:

$$HHI_3=\sum_i^I(1-q_i)^*(1/f_i)^*p_i^2+\sum_{j=1}^I\sum_{i=1}^I p_ip_j\sigma_{ij},,$$

p_i: the share of energy i in the total energy supply.
q_i: the share of energy i in the total indigenous energy supply.
f_i: the supply capacity of energy i.
σ_{ij}: the covariance of the prices of energy i and j.

The comparison of the diversity indices in this study is shown in Table 3.

5. Empirical analysis of diversity index-a case study of Taiwan

5.1. Parameter setting and data adjustment

Considering the properties of various energies, this study divides different forms of energy into eight categories: coal and coal products, crude oil and petroleum products, natural gas, waste and biofuel, conventional hydropower, nuclear power, wind power, solar power and thermal power. In the calculation of diversity indices, the classification of energy will influence the value of the index. However, the purpose of this study is to compare the relative impact of changes in the energy structure on the index. The focus will be on the operational and market characteristics of various energies. Therefore, the classification will be based on price category and operating characteristics. The influence of energy classifications on the index will be overlooked in this study.

The calculations in this study are based on statistical data and indicators on Taiwan's energy supply and demand published by MOEABOE [101]. Regarding energy supply capacity (f_i), the technologies of traditional fossil fuels are mature enough to operate at full capacity, except in cases of system failure. However, certain types of renewable energy are intermittent, such as wind and photovoltaic power, and are not continuously available due to natural weather conditions. Such impacts on the reliability of energy systems must be taken into consideration and can be divided according to the length of time:

(1) In the ultra-short-term (minutes to hours) and short-term (day), the system focuses on real-time monitoring and control of renewable energy equipment to reduce the impact on the reliability of energy system. The availability of “instantaneous dispatch units” and the ability to forecast instant contributions of renewable energy is the main concern.
(2) In the mid- to long-term (month to year), the focus will be the contribution of renewable energy's installed capacity to the electricity load, especially the peak load.

The purpose of this study is to investigate the annual change of diversity indices, and the focus is on the contribution of renewable energy's installed capacity to maintain an energy system. Therefore, this study uses the net peaking capacity to estimate the energy supply capacity. The net peaking capacity is the maximum load that an electrical generator can carry under normal service conditions. For conventional energy sources, including the

Table 3
Correlation between the index value and diversity and comparison of characteristics of diversity indices

Index	Value/diversity variation correlation	Comparison of characteristics
HHI_1	↓/↑	Having been applied broadly, and regarding each type of energy as independent, as the result, energy security increases when the diversity elevates
SWI_1	↑/↑	
HHI_2	↓/↑	Emphasizing the impacts of the availability of indigenous energy and various imported energy on energy security
SWI_2	↑/↑	
HHI_3	↓/↑	Considering the complementary and substitutive relationships between energies and their impacts on energy security; integrating the concept of risk into energy diversity index

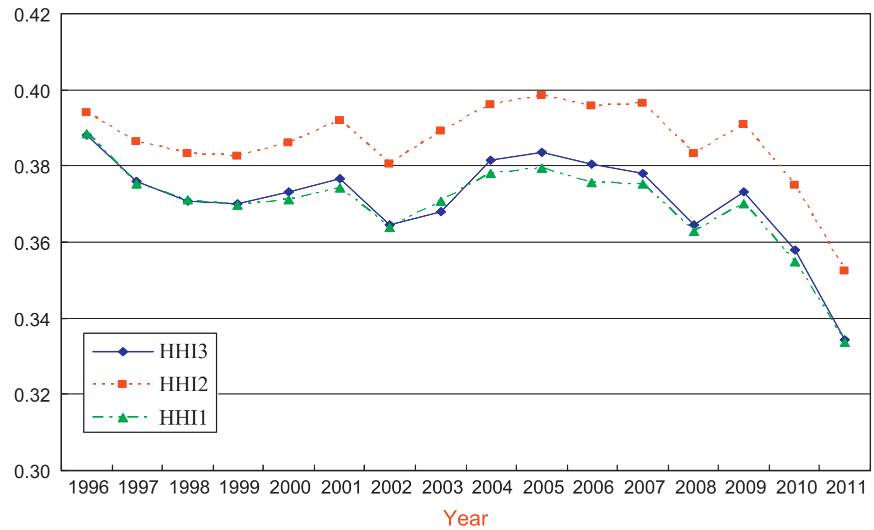

Fig. 2. Results of the HHI_1, HHI_2 and HHI_3.

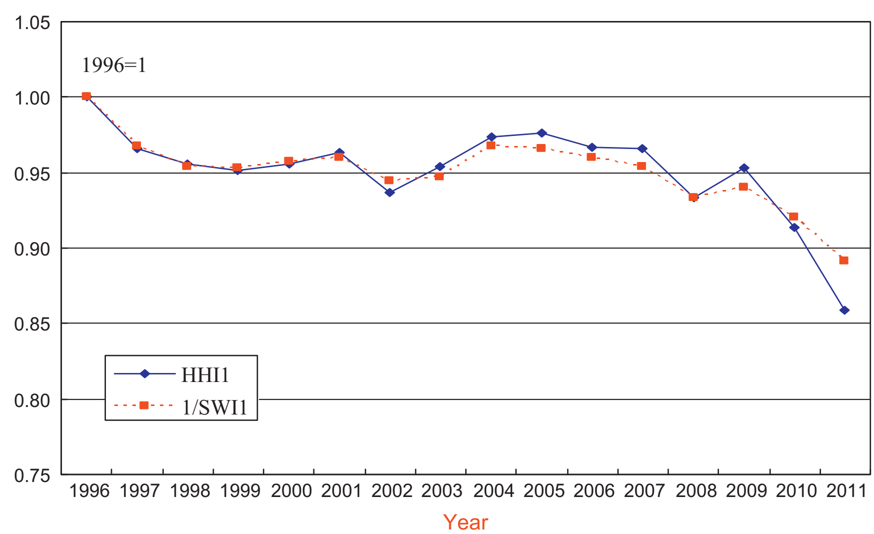

Fig. 3. Comparisons of the HHI_1 and SWI_1.

technologically mature and stable fossil and nuclear energy, the estimation of energy supply capacity only needs to consider the possible setback of sudden failure and routine maintenance on thermal and nuclear power generation units. In addition, biofuel can be treated as a conventional energy source because it can secure raw material supplies through policy support. As for other renewable energies, such as hydropower, wind power and solar power, their actual supply capacity equals the contribution of their installed capacity to the electrical load, and thus they can be represented by net peaking capacity. The net peaking capacity can not only reflect the improvement in renewable energy technologies but also the changes in natural conditions under the impact of climate change. This study also calculates the price correlation coefficient between energies by the average imported price of coal, crude oil and LNG from 2007 to 2011 in Taiwan.

5.2. Result and analysis

From the calculation results using data from 1996 to 2011 (see Fig. 2), we can see that HHI_1 reached its maximum value in 1996, and the energy supply structure concentrated in crude oil and petroleum products; coal and coal products, and nuclear energy accounted for 94.17% of the total. Later, the share of nuclear energy gradually decreased, and the ratio of natural gas increased. The HHI_1 showed fluctuations before 2009. In this period, over 80% of the energy supply came from crude oil and petroleum products and coal and coal products and reached the interval high of 82.42% in 2005. Adding nuclear energy and natural gas, these four energies accounted for 98.46% of the energy supply in 2005, which was highly concentrated and brought HHI_1 to its second highest level. Given the energy diversity policy direction to increase natural gas use and actively promote renewable energy in Taiwan, in 2011 both energies reached their all-time highest levels of 11.78% and 0.47%. This increase made HHI_1 drop to its lowest level observed, showing that the initial result of the energy diversity policy has improved Taiwan's energy security.

SWI_1 and HHI_1 showed similar diversity trends each year (see Fig. 3), but the trends from 2004 to 2005 were different. While the SWI_1 showed an improving trend, the HHI_1 showed a deteriorating trend. This decrease occurred because the proportion of coal and coal products decreased while conventional hydrodynamic and nuclear energy increased. The proportion of wind power also increased in the same year. From the relative abundance perspective, the SWI emphasizes rare species, and conventional

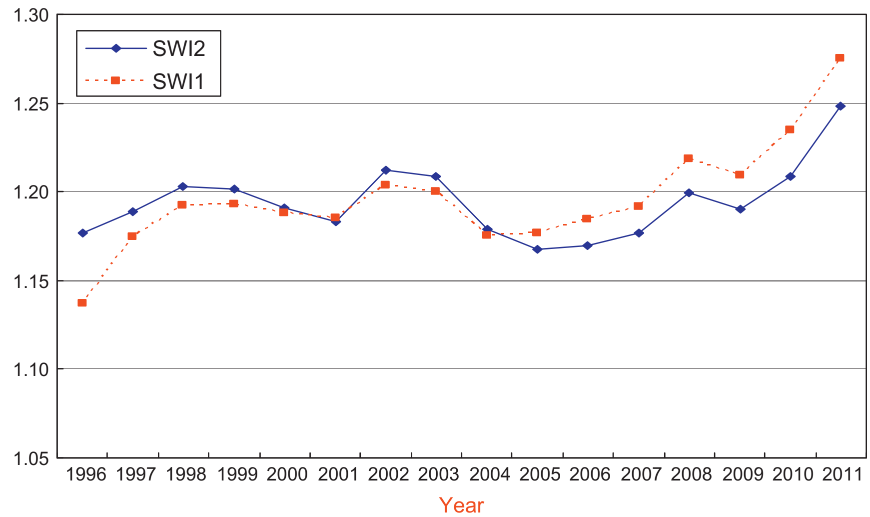

Fig. 4. Results of the SWI_1 and SWI_2.

hydrodynamic and wind power are energies with lower relative shares; thus, the value of the *SWI* appeared to be improving. The value of HHI_1 decreased because the proportion of coal and coal products also decreased. Comparing the SWI_1 and HHI_1 with the maximum value of the right categories (*SWI*(2.08), *HHI*(0.13)), both indices fall on the lowest grade.

As for the results shown by the energy supply diversity and reliability index (I_2), the HHI_2 and HHI_1 were similar, although the value of HHI_2 was greater than HHI_1, showing that the diversity is lowered when the impact of indigenous energy on system reliability is considered. The *HHI* index emphasizes options making up a higher share of the structure; thus, the renewable energy with lower proportions could not alter the HHI_2 trend with its indigenous characteristics (although wind power and solar power are lower in reliability). The results of SWI_2 and SWI_1 are difference in trend and degree (see Fig. 4). Between 1996 and 2000, Taiwan still produced indigenous coal, and the production of indigenous natural gas was higher. As a result, the value of SWI_2 is higher than $SWI_{1.}$ Later, coal mining stopped, and the indigenous production of natural gas also decreased such that the value of SWI_2 was lower than SWI_1 after 2005. The proportion of such renewable energies as waste and biofuel, wind and solar power also gradually increased after 2005. Accordingly, the diversity of SWI_2 and SWI_1 improved. However, this study not only focused on the indigenous characteristics of renewable energy but also on its impact on system stability. As noted above, due to technological and environmental constraints, solar and wind power are less reliable, which will reduce energy security. As a result, the value of the SWI_2 did not surpass the SWI_1 along with the higher proportion of renewable energy. As mentioned earlier, the proportion of wind power increased between 2004 and 2005, resulting in SWI_2 showing a decreasing trend, contrary to the increasing trend of $SWI_{1.}$ This finding demonstrated the differences in the results between diversity and reliability indices when the impact of each energy on energy security is considered, as is emphasized in this study. From the policy aspects, the renewable energy is actively promoted in Taiwan; this will increase diversification and proportion of indigenous energy and in turn increase energy security. Due to the fact that there are still technological limits to renewable energy, thus renewable energy cannot be considered as the main energy source, and therefore proportion of renewable energy's should be restricted for the possible impact on energy supply stability.

As for the results of energy supply diversity and the reliability variance index (I_3), the results of the HHI_3, $HHI_{2,}$ and HHI_1 were similar, but the average value of HHI_3 was lower than that of HHI_2 and near HHI_1, showing that diversity increased after the price correlation coefficient was adopted between different energies. Except for a small amount of natural gas, which accounted for approximately 0.2% of the total supply in 2011, the coal, crude oil and natural gas supply depended mainly on importation. All three energies showed a positive correlation with international energy prices. Uranium fuel is positively correlated with coal and negatively correlated with crude oil and natural gas, which indicates that nuclear power has the effect of lowering risks in crude oil and natural gas. The price of renewable energy sources, such as conventional hydrodynamic, waste and biofuel, and wind, solar and thermal power, does not co-vary with fossil fuels and nuclear energy. This price is considered risk neutral and has the effect of reducing energy security risks and to increase energy security. Between 2006 and 2007, there was a slight decrease in the value of HHI_3 and HHI_1, while the value of HHI_2 slightly increased. In the supply structure of that period, the share of coal and coal products and nuclear energy decreased slightly, the share of natural gas and wind power increased slightly and the share of waste and biofuel increased significantly. Because waste and biofuel is renewable and more stable than wind power and solar energy, it is helpful for diversity and energy security. All in all, energy diversity and security both improved in that period; thus, HHI_3 and $HHI_{1,}$ as compared to $HHI_{2,}$ can more accurately interpret diversity and energy security.

6. Conclusions and suggestions

Diversity can improve energy system stability through increasing selection options. Energy issues are closely related with economic development, scientific research and development, socio-cultural issues, environmental protection and international politics. The complexity and uncertainty of energy issues can cause difficulties and blind spots in decision-making. In this case, a diversified energy portfolio can hedge against fluctuations in price and provide comparably stable and lower risk energy for the energy supply system.

The optimization of an energy mix in the context of energy security has always been the focus of the energy decision-making process. Under the constraints of natural resource endowments and domestic and international energy, political and economic situations, all countries attempt to optimize their future energy diversity portfolio to secure an energy supply, maintain affordable energy prices and reduce environmental impacts. Therefore, there

should be a description of how energy diversity can lower energy security risks. This study improved the present *HHI* and *SWI* diversity indices ability to interpret energy security by proposing the “Energy Supply Diversity and Reliability Index” and “Energy Supply Diversity and Reliability Variance Index” to complement the impact of the energy diversity portfolio on lowering the risks of supply shortages and cost fluctuations.

Confined by the emphasis of the *HHI* on abundant options and the *SWI* on rare options, the modified result of the “Energy Supply Diversity and Reliability Index” is more significant on *SWI*. However, it is expected that as the proportion of renewable energy increases, and the reliability of the system is enhanced through the technological progress of wind and solar power in improving net peaking capacity, the explanatory power of the index will be more significant. Additionally, when considering the covariance between various energies, the “Energy Supply Diversity and Reliability Variance Index” and the original *HHI* exhibit similar trends, but their variation differentiates as the share of indigenous energy increases. After discussing reliability and covariance, the index could better recognize the impact of energy diversity on lowering energy security risks.

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